

# REDETERMINATION OF THE Sm-Nd AGE AND INITIAL $\epsilon_{\text{Nd}}$ OF LUNAR TROCTOLITE 76535: IMPLICATIONS FOR LUNAR CRUSTAL DEVELOPMENT.

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**Introduction:** Lunar troctolite 76535 is an old lunar rock predating the era of the lunar cataclysmic bombardment, but its radiometrically determined ages have been discordant [1-3]. The most recent multi-chronometer study [4] gave preferred ages of  $4226 \pm 35$  Ma and  $4236 \pm 15$  Ma from a  $^{207}\text{Pb}/^{206}\text{Pb}$  isochron and an U-Pb upper concordia intercept, resp. We derive an age of  $4323 \pm 64$  Ma from Sm-Nd data reported by [4] for the bulk rock and three mineral separates. They derived an age of  $\sim 4.38$  Ga from combined Rb-Sr data [3,4] by omitting data for olivine separates.  $^{39}\text{Ar}$ - $^{40}\text{Ar}$  ages of  $\sim 4.2$  Ga are summarized by [5].

New  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  data presented here give an age of  $4335 \pm 71$  Ma in agreement with the Sm-Nd age from [4], whereas  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  data give a model age  $T_{\text{LEW}} = 4439 \pm 22$  Ma. Further, initial  $\epsilon^{143}\text{Nd}$  for 76535 conforms to the  $^{143}\text{Nd}$  evolution expected in an urKREEP [6] reservoir, consistent with inheritance of urKREEP Sm-Nd systematics via assimilation. We show that urKREEP Sm-Nd systematics require the lunar initial  $\epsilon^{143}\text{Nd}$  to exceed the Chondritic Uniform Reservoir (CHUR) value [7], but are consistent with evolution from initial  $\epsilon^{143}\text{Nd}$  like that of the HED meteorite parent body as defined by a  $4557 \pm 20$  Ma internal isochron for the cumulate eucrites Y-980433 and Y-980318 [8].

**$^{147}\text{Sm}$ - $^{143}\text{Nd}$  isochron:** Nine  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  analyses determine an isochron corresponding to an age of  $4335 \pm 71$  Ma and  $\epsilon^{143}\text{Nd} = 0.23 \pm 0.44$  (Fig.1). Two data points lie sufficiently far from the fitted isochron to warrant their exclusion from the regression. With these exceptions, the data lie within  $\sim 1$   $\epsilon$ -unit of the isochron. The MSWD = 22 and may represent response of the Sm-Nd system to post-crystallization events.

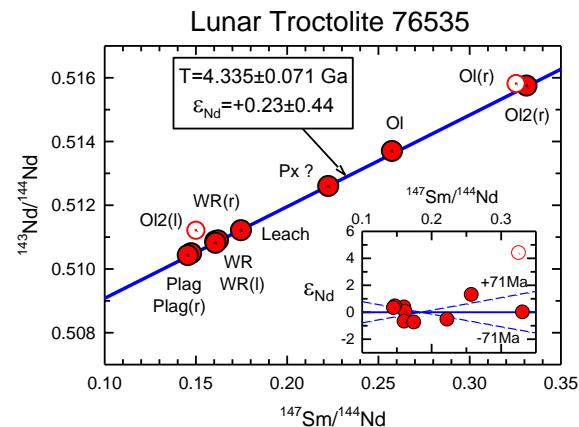


Figure 1.  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  isochron for 76535.

**$^{146}\text{Sm}$ - $^{142}\text{Nd}$  isochron:** New  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  data are shown in Fig. 2. Ten data points determine an isochron slope corresponding to initial  $^{146}\text{Sm}/^{144}\text{Sm}$  ( $I(\text{Sm})$ ) =  $0.0034 \pm 0.0005$  with MSWD = 1.9. A model age  $T_{\text{LEW}} = 4439 \pm 22$  Ma is calculated by reference to  $I(\text{Sm}) = 0.0076$  [9] for the 4558 Ma angrite LEW 86010 [10] and a  $^{146}\text{Sm}$  half-life of 103 Ma [11].

**Crystallization Age:** We suggest that the Sm-Nd chronometers most accurately give the crystallization age of 76535. We note that a “three-point”  $^{207}\text{Pb}/^{206}\text{Pb}$  isochron age of  $4343 \pm 72$  Ma is derivable from the data of [4] by regressing their whole rock residue (WR) data with the data for both plagioclase separates PL-1 and PL-2 (cf. [4], Fig. 5), as corrected for the measured Pb blanks. Alternatively, ages of  $4338 \pm 30$  Ma for PL-1 plus PL-2 alone and  $4226 \pm 35$  Ma for WR, PL-1, and OL-P were reported by [4]. Considering the Pb data for WR plus both plagioclase samples may be more appropriate. Pb should be more compatible in plagioclase than in olivine or pyroxene, but the blank-corrected Pb concentration in Ol-P (40.1 ppb) exceeded that in PL-2, the reverse of expectation. Moreover, the percentage of Pb blank correction for Ol-P (3.7%) exceeded that for PL-2 (2.3%). Further, the blank correction for PL-2 was comparable to that for WR, and only  $\sim 2.3$  times that for PL-1. Finally, lower blank-corrected Pb concentration for PL-2 (26.8 ppb) than for PL-1 (44.2 ppb) provides no rationale for further blank correction [4].

**Significance of (T,  $\epsilon_{\text{Nd}}$ ) relationships:** Fig. 3 compares (age(T),  $\epsilon^{143}\text{Nd}$ ) parameters for 76535 to other samples that are enriched in the urKREEP component. Data are from JSC (78236 [12], 72275 [13], 76535 [14]), and UCSD (15386 [15]).  $^{143}\text{Nd}$  evolution in the urKREEP reservoir(s) is shown for  $\mu =$

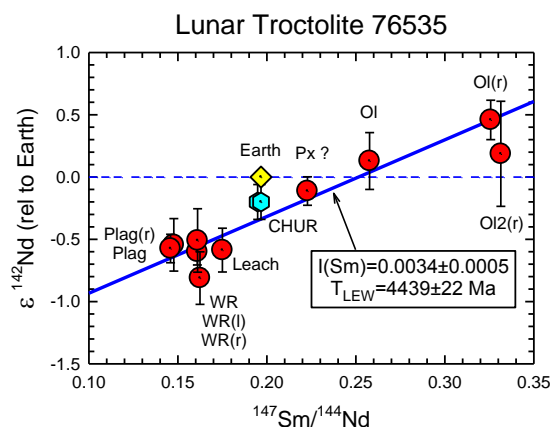


Figure 2.  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  isochron for 76535.

$^{147}\text{Sm}/^{144}\text{Nd} = 0.172$  (red line). The Apollo samples are either KREEP basalts or Mg-suite rocks. KREEPy mare basalt NWA 2977, probably derived from the Procellarum KREEP Terrane (PKT), extends the ( $T, \epsilon^{143}\text{Nd}$ ) correlation to  $\sim 3.1$  Ga ago. That these diverse lunar rock types exhibit the same pre-magmatic, sub-chondritic, radiogenic ingrowth of  $^{143}\text{Nd}$  in their source reservoirs is consistent with their assimilation of large proportions of their Nd from “semi-infinite” sources of urKREEP residua. The  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio in materials from the last  $\sim 5\%$  crystallization of parent magma systems of bulk lunar composition is expected to show little variation (e.g., [16]). In the case of a global Lunar Magma Ocean (LMO), the ( $T, \epsilon^{143}\text{Nd}$ ) correlation can be extrapolated to the time when the LMO had reached  $\sim 90\text{--}95\%$  crystallization. For rapid LMO crystallization near the solar system age of  $\sim 4568$  Ma, an initial lunar  $\epsilon^{143}\text{Nd} = 1.1 \pm 0.2$  is predicted, within the error limits of initial  $\epsilon^{143}\text{Nd}$  for the paired cumulate eucrites Y-980433/318 (Y98) [8]. Hf-W systematics constraining crystallization of the LMO to  $62(+90, -10)$  Ma after formation of the solar system [23] constrain  $\epsilon^{143}\text{Nd}$  to the range  $+0.6$  to  $+0.9\epsilon$ .

**Two-stage model for Nd-isotopic evolution:** Fig. 4 models evolution of  $\epsilon^{143}\text{Nd}$  and  $\epsilon^{142}\text{Nd}$  in urKREEP source(s) from assumed initial values. For initial  $\epsilon^{143}\text{Nd}$  like that in the Y98 cumulate eucrites, the modeled evolution prior to crystallization of 76535 gives  $\mu = 0.159$ , nearly identical to measured  $\mu = 0.161$  post-crystallization. Similar  $\mu$ -values of  $\sim 0.15\text{--}0.17$  can account for evolution to  $\epsilon^{142}\text{Nd}$  for 76535 for a non-chondritic, Earth-like initial  $\epsilon^{142}\text{Nd}$ . These results illustrate the possibility of (a) early lunar formation, accompanied by early formation of LREE enriched urKREEP, and (b) measured  $\epsilon^{142,143}\text{Nd} > \text{CHUR}$  for lunar highland rocks.

**Implications:** Although these Nd-isotopic results for troctolite 76535 are permissive of a “young”,  $\sim 4.4$

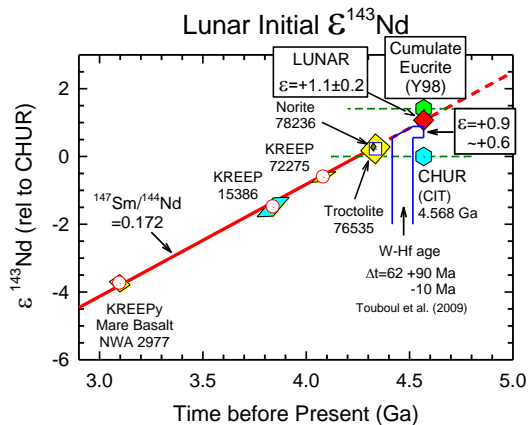


Figure 3. ( $T, \epsilon^{143}\text{Nd}$ ) for urKREEP-enriched samples including mare basalt NWA 2977.

Ga moon with initial Nd isotopic composition near chondritic values, the lunar age must be greater than that of the oldest zircon,  $4417 \pm 6$  Ma [17]. Also, the young  $4360 \pm 3$  Ma age of 60025 [18] when viewed in combination with concordant Sm-Nd and Rb-Sr ages of  $4.47 \pm 0.07$  Ga for lunar anorthosite 67075 [19,20] and Sm-Nd data for bulk anorthosites suggests variability in the ages of lunar anorthosites. Key observations are: (a) urKREEP reservoirs were produced contemporaneously, or nearly so, in diverse lunar locations, (b) urKREEP-enriched Mg-suite rocks are contemporaneous, or nearly so, with lunar anorthosites. These observations can be explained by an initial LMO followed by post-magma-ocean genesis of lunar anorthosites [21] as well as of Mg-suite lunar highland rocks (e.g., [22]).

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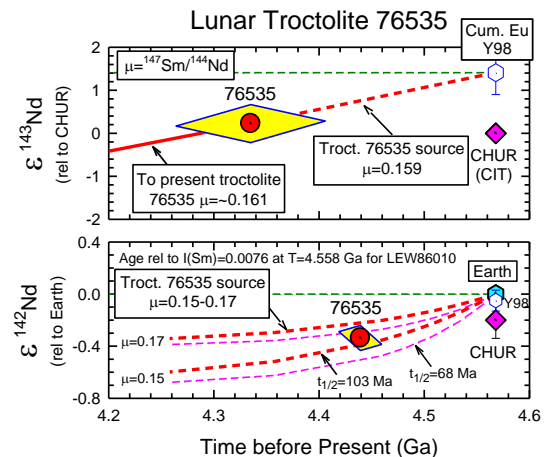


Figure 4. Hypothetical isotopic evolution for  $^{143}\text{Nd}$  (top) and  $^{142}\text{Nd}$  (bottom) in a simple two-stage model.